(Ga,Mn)As on patterned GaAs(001) substrates: Growth and magnetotransport

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Abstract

A new type of (Ga,Mn)As microstructures with laterally confined electronic and magnetic properties has been realized by growing (Ga,Mn)As films on [1$\bar{1}$0]-oriented ridge structures with (113)A sidewalls and (001) top layers prepared on GaAs(001) substrates. The temperature- and field-dependent magnetotransport data of the overgrown structures are compared with those obtained from planar reference samples revealing the coexistence of electronic and magnetic properties specific for (001) and (113)A (Ga,Mn)As on a single sample.

Key words: GaMnAs, Patterned substrate, MBE, (113)A, Magnetotransport
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The dilute magnetic semiconductor (Ga,Mn)As, being compatible with conventional semiconductor technology, is considered a potential candidate for spintronic applications and has been intensely studied during the past few years [1,2]. So far, (Ga,Mn)As layers were exclusively grown on planar substrates by low-temperature molecular-beam epitaxy (LT MBE) where the structural, electronic, and magnetic properties of the films have been shown to depend on the growth conditions and on the crystallographic orientation of the substrate [3,4,5,6]. Lateral micro- or nanostructures for magnetotransport and magnetization studies were prepared on homogeneous layers in a "top-down" procedure using various etching techniques. In order to introduce an additional degree of freedom in the development of new functional (Ga,Mn)As-based structures, we choose a completely different "bottom-up" approach. We pick up a method widely used in the past to realize laterally confined semiconductor microstructures in a single growth run, namely the growth of epilayers on patterned substrates. More precisely, ridge structures exhibiting (001) top planes and (113)A sidewalls were overgrown with (Ga,Mn)As films yielding (Ga,Mn)As layers with areas of different substrate orientation on a single sample.

For this purpose, mesa stripes oriented along [1$\bar{1}$0] with (113)A sidewalls were prepared on semi-insulating VGF GaAs(001) substrates by conventional photolithography techniques and selective wet chemical etching. The sidewall orientation was controlled by varying the composition of a $NH_4OH:H_2O_2:H_2O$ solution. Etch depths between 0.2 and 0.6 μm were realized resulting in widths of the (113)A facets from 0.5 to 1.4 μm. The width of the (001) top plane was varied from 0 to 15 μm. After removal of the photoresist the patterned substrates and planar (001) and (113)A reference substrates were mounted with In on the same Mo holder. Then they were introduced into a RIBER 32 MBE chamber equipped with a conventional Knudsen cell and a hot-lip effusion cell providing

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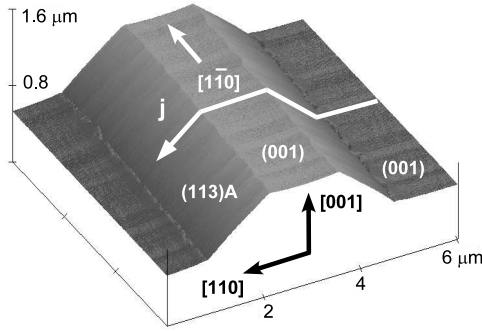
Fig. 1. AFM micrograph of an overgrown ridge structure with (113)A sidewalls.
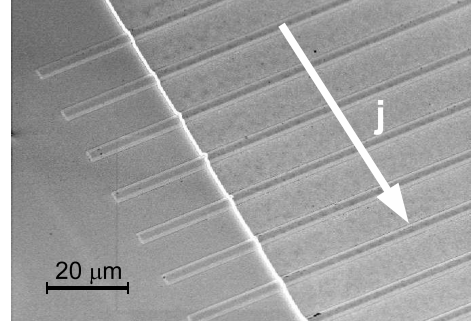

Fig. 2. SEM micrograph of a Hall bar (section) carrying a series of overgrown ridges. The edge of the Hall bar is seen as a white line.

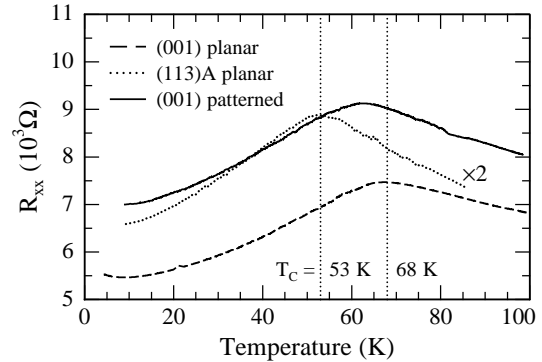Fig. 3. Estimate of the Curie temperatures T_C from the peak positions of the temperature-dependent resistances R_{xx}.

the Ga and Mn fluxes, respectively. A valved arsenic cracker cell was operated in the non-cracking mode to supply As_4 with a V/III flux ratio of about 5. After thermal deoxidation under As_4 overpressure, a GaAs buffer layer around 30 nm thick was deposited at a temperature of $T_s \approx 580$ °C (conventional substrate temperature for GaAs). Then the growth was interrupted and T_s was lowered to ~ 250 °C. Finally, (Ga,Mn)As layers with Mn contents up to 5% and a thickness of 40 nm were grown. Fig. 1 shows as an example the surface topography of an overgrown 1.5-μm-broad ridge imaged by scanning atomic force microscopy (AFM). It reveals smooth (001) and (113)A facets with sharp edges as well as a bump-like shape at the (113)A/(001) facet transition due to the migration of Ga adatoms during the high-temperature growth of the GaAs buffer layer [7]. No indication of the presence of MnAs clusters is observable.

The electronic and magnetic properties of the samples under study were investigated by means of magnetotransport measurements, representing a powerful tool for the characterization of ferromagnetic semiconductors. For this purpose, Hall bars were prepared on the patterned samples and on the planar (001) and (113)A reference samples with the current direction along [110] and [33$\bar{2}$], respectively. The Hall bars on the patterned samples carry series of evenly spaced parallel ridges of equal dimension oriented perpendicular to the current direction. A scanning electron microscopy (SEM) micrograph showing a section of such a Hall bar is presented in Fig. 2.

In the following, we focus on a sample with 1.5-μm-broad mesa stripes (see Fig. 1) and a Mn content of 5%. The Curie temperatures of the structured layer and the corresponding reference layers were estimated from the temperature-dependent longitudinal resistance R_{xx} with an external magnetic field of 100 mT applied along the [001] direction. From the peak positions of the measured curves depicted in Fig. 3, values of ~ 68 K for the (001) and ~ 53 K for the (113)A reference layers are deduced. These values are consistent with the hole densities of 3×10^{20} cm^{-3} and 1.5×10^{20} cm^{-3}, respectively, determined from high-field (up to 14.5 T) magnetotransport measurements at 4.2 K. The curve recorded from the patterned sample (solid line) exactly represents a superposition of the (001) and (113)A curves (dashed and dotted lines, respectively) weighted according to the area ratio of 82:18 between the (001) and (113)A planes on the Hall bar.

Another, even more obvious evidence for the coexistence of (001)- and (113)A-specific properties in the structured (Ga,Mn)As layer is obtained from the field dependence of R_{xx} measured at 4.2 K. In Fig. 4 the relative changes $\Delta R_{xx}/R_{xx,0}$ are plotted as a function of the magnetic field strength in
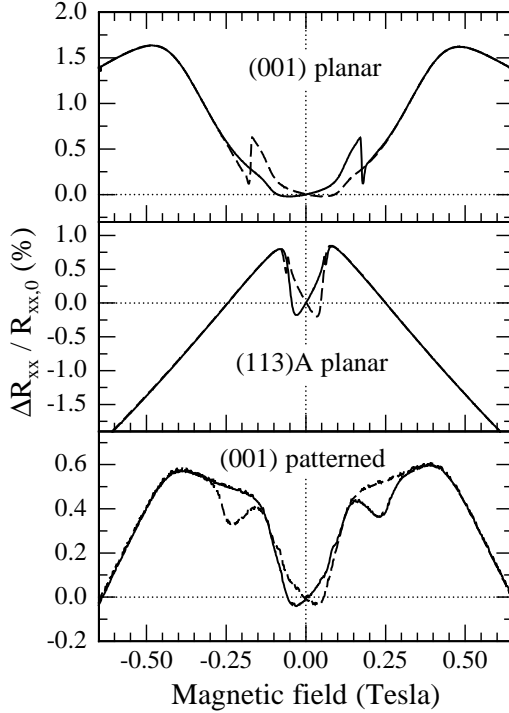
Fig. 4. Relative change of the longitudinal magnetoresistances at 4.2 K measured as a function of magnetic field strength with the field $\boldsymbol{H}$ oriented along [001].

patterned sample clearly exhibits a superposition of both features confirming the simultaneous presence of areas with (001)- and (113)A-specific properties. The jump in the curve of the (001) planar sample at ± 0.18 T is due to magnetic anisotropy and arises from a sudden movement of $\boldsymbol{M}$ caused by a discontinous displacement of its equilibrium orientation.

In summary, (Ga,Mn)As films of high crystalline quality were grown by LT MBE on $[1\bar{1}0]$-oriented ridges with (113)A sidewalls prepared on GaAs(001) substrates. Magnetotransport measurements clearly reveal the lateral coexistence of areas with (001)- and (113)A-specific properties opening the prospect of a new degree of freedom in the development of (Ga,Mn)As-based spintronic devices. (Ga,Mn)As microstructures realized in this way may be easily overgrown with further layers without the need to interrupt the MBE growth.

the range from -0.6 to 0.6 T for both, up-sweeps (solid lines) and down-sweeps (dashed lines). For all samples the field $\boldsymbol{H}$ was applied along [001]. For sufficiently high magnetic fields the measured curves are dominated by a negative magnetoresistance which has been ascribed to spin-disorder scattering [1] and/or suppression of weak localization [8]. The behaviour of R_{xx} at low fields is governed by an anisotropic magnetoresistance and by magnetic anisotropy. The longitudinal and Hall resistances in (Ga,Mn)As are well known to sensitively depend on the orientation of the magnetization $\boldsymbol{M}$ with respect to the current direction $\boldsymbol{j}$ and the crystallographic axes [9,10]. At zero magnetic field the magnetization is almost parallel to the (001) plane, even in the case of the (113)A-oriented sample [11]. With increasing field a reorientation of $\boldsymbol{M}$ along $\boldsymbol{H}$, i.e., along the [001] direction takes place resulting in an increase of R_{xx}. Whereas in the (001) planar sample the transition from anisotropic to negative magnetoresistance occurs at about ± 0.5 T, the transition in the (113)A planar sample appears at ± 0.1 T. The

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